Draft Interim Review of PRM-50-93/95 Issues Related to Minimum Allowable Core Reflood Rate

Disclaimer:

Public availability of this draft interim review is intended to inform stakeholders of the current status of the NRC's review of the issues raised in PRM-50-93/95. This draft interim review is subject to further revisions during resolution of PRM-50-93/95. The NRC is not soliciting public comments on these interim conclusions, and will not provide a formal response to any comments received. The NRC's findings on PRM-50-93/95 issues will not be final until the NRC publishes a notice of final action on this petition for rulemaking in the *Federal Register*.

1.0 Issues Raised in the Petitions and Associated Comments

A petition for rulemaking was docketed as PRM-50-93 on November 17, 2009 (M. Leyse, 2009). The petition is requesting revisions to section 50.46 of Title 10 of the *Code of Federal Regulations* (10 CFR) "Acceptance criteria for emergency core cooling systems for light-water nuclear power reactors" and to 10 CFR Part 50, Appendix K "ECCS Evaluation Models" as well as associated regulatory guidance. The petition claims that several aspects of the existing regulations are non-conservative. In particular, the petition states:

> Additionally, it can be extrapolated from experimental data that, in the event a LOCA, a constant core reflood rate of approximately one inch per second or lower (1 in./sec. or lower) would not, with high probability, prevent Zircaloy fuel cladding, that at the onset of reflood had cladding temperatures of approximately 1200°F or greater, from exceeding the 10 C.F.R. § 50.46(b)(1) PCT limit of 2200°F.

The petition requests "that the NRC make a new regulation stipulating minimum allowable core reflood rates, in the event of a loss-of-coolant accident ('LOCA')."

This report is the U.S. Nuclear Regulatory Commission (NRC) staff's interim evaluation of certain assertions in petition for rulemaking PRM-50-93/95 regarding the stipulation of a minimum allowable core reflood rate as part of the regulations.

2.0 Supporting Comments and Information Provided in the Petitions

The petition cites as a basis for the proposed rule change FLECHT Test 9573. This particular test used a Zircaloy bundle and was conducted with an initial maximum cladding temperature of 1970 degrees F. The flooding rate was nominally 1.1 inch/sec. A post-test inspection of the bundle found there to be severe local damage near a Zircaloy spacer grid at the 7-ft elevation due to temperatures in excess of 2500 degrees F. Several possible causes of the high temperatures were cited, with metal-water reaction of Zircaloy being a likely candidate (Cadek et al., 1971).

The petition states on page 12:

> Petitioner believes that the "the impression left from run 9573" includes the fact that run 9573 had a low coolant flood rate; it had the lowest flood rate of the four FLECHT Zircaloy tests. It also had the lowest initial cladding temperature, before flood, of the four Zircaloy tests. Therefore, it is highly probable that run 9573 incurred autocatalytic oxidation, because it had a low flood rate.

The petition further claims:

> It would be reasonable to postulate that if run 9573 were repeated—with the same or a lower coolant flood rate, yet with lower initial cladding temperatures (that in the event of a LOCA, would occur at the beginning of reflood at current and/or proposed PWRs) and a lower power level (within the operational range of current and/or proposed PWRs)—that the fuel assembly would still incur autocatalytic oxidation and be destroyed, because run 9573 had the lowest flood rate of the four Zircaloy tests. Furthermore, it is likely that such a test would produce valuable heat transfer information.

As additional support for the request for a limit on the reflood rate, the petition further cites results from NRU tests (page 18). The petition notes that NRU tests with reflood rates less than or equal to 1.0 inch/sec had large temperature increases. The peak cladding temperatures in those tests remained below 2200 degrees F, but these tests started with relatively low initial cladding temperatures. The petition hypothesizes that if these tests had started with higher initial cladding temperatures, these assemblies "with high probability, would have incurred autocatalytic (runaway) oxidation, clad shattering, and failure —like FLECHT run 9573."

3.0 Background on Reflood LOCA Hydraulics

There are several parameters that are known to have an important effect on reflood in a light water reactor (LWR). Experimental studies such as FLECHT (Lilly, et al., 1977), FLECHT-SEASET (Lee, et al., 1982), Achilles (Pearson and Denham, 1989), NRU (Mohr, et al.,1981) and RBHT (Hochreiter, et al., 2012) have each demonstrated that the peak cladding temperatures and behavior of reflood hydraulics depends on several parameters including reflood rate, coolant subcooling, and pressure. In addition, initial and boundary conditions due to geometry and operation also affect LOCA behavior. These include but are not limited to the rod bundle design, bundle power, power shape and power decay rate.

The parametric effects of many of these parameters were considered in the evaluation by Lee et al. (1982). Reflood rate was found to be an important parameter, with peak cladding temperatures increasing as the reflood rate decreases. However, other parameters were also found to have significant effects on the peak cladding temperature or quench time of the rod bundle. Initial cladding temperature and initial rod power likewise were found to have important effects. Peak cladding temperatures increased with increasing initial temperature or initial power. Other parameters, such as pressure and coolant subcooling were found to have a relatively weak influence on peak cladding temperature, but could have important effects on the bundle quench time (which may influence the duration of time over which significant metal-water reaction occurs).

Because numerous parameters have an effect on reflood hydraulics, no single parameter completely controls the peak cladding temperature for a particular transient. Basing a conclusion on any single parameter can be misleading. Part of the basis for the petition's request for a limit on reflood rate, is the significant temperature increases observed in the NRU reflood tests. Starting from initial cladding temperatures less than 1000 degrees F, several NRU tests produced temperature increases of over 1000 degree F. The petition cites NRU test 127 and 130 as examples. The petition appears to imply that similar temperature increases would occur if the initial cladding temperatures had been 1200 degrees F or more. This is not correct, however. Thermal radiation becomes more important in transferring heat away from hot spots, and as rod temperatures increase the temperature difference between the cladding and the coolant increases. Figure 1, from Lee et al. (1982), shows the effect of initial cladding temperature on temperature rise from tests in three experimental facilities. As the initial cladding temperature increases, the overall temperature rise <u>decreases</u>. Thus, contrary to the claim made in the petition, "extrapolation" of data does <u>not</u> show "with high probability" that peak cladding temperatures will exceed 2200 degrees F.

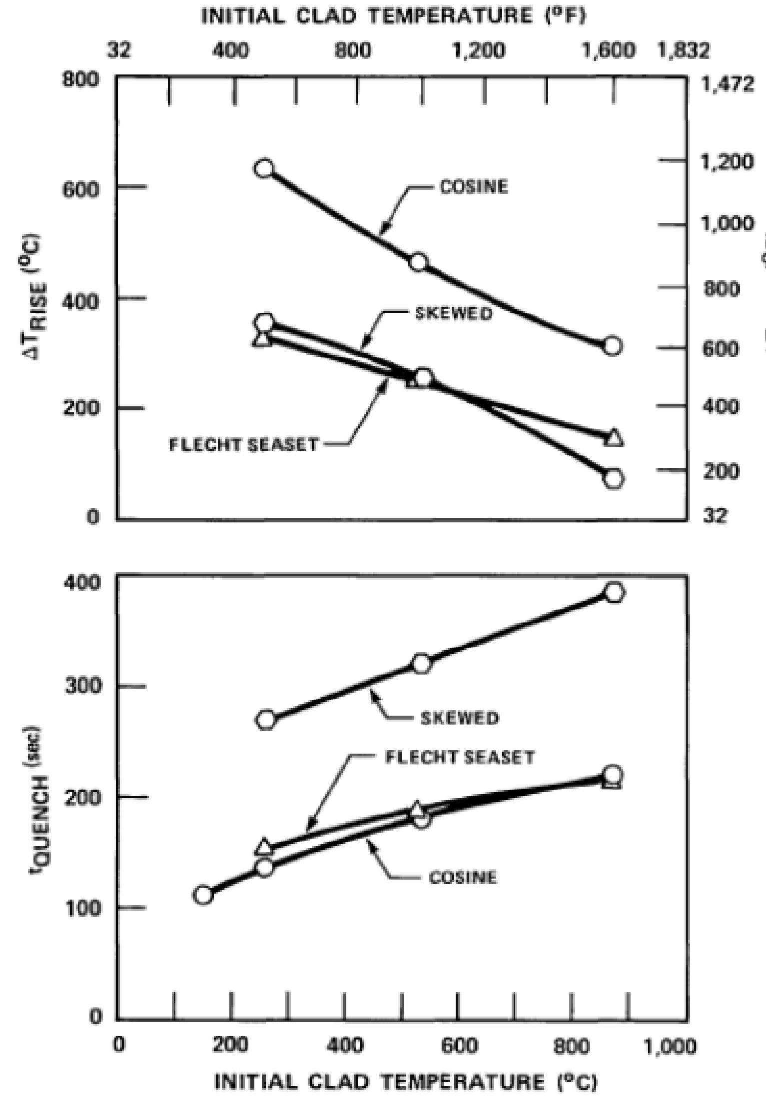

Figure 1. Initial Clad Temperature Effect of Temperature Rise and Quench Time. (Figure 3-23 from Lee et al. (1982)

4.0 Consideration of Metal-Water Reaction

The FLECHT, FLECHT Top-Skewed Power, and FLECHT-SEASET results shown in Figure 1 were not conducted with Zircaloy as the cladding material. Thus, there remains a possibility that as the cladding temperature exceeds 1000 degrees C (1832 degrees F) and the metal-water reaction rate becomes significant, this might increase the overall temperature rise in the bundle. While the NRU bundle did have Zircaloy cladding, the initial cladding temperatures were generally lower than those in counterpart experiments in other facilities, as noted in the petition. To examine the effect of initial cladding temperature on reflood where metal-water reaction is a concern, a sensitivity study was conducted using TRACE with simulations of FLECHT Test 9573. As noted previously, FLECHT Test 9573 had a forced reflood rate of 1.1 inch/sec (0.02794 m/sec). But, because it initiated with an initial cladding temperature of 1970 degrees F, temperatures quickly exceeded 2200 degrees F, damaging the bundle. TRACE simulation of Test 9573 showed reasonable agreement with available data, with TRACE exceeding the measured maximum cladding temperature 18 seconds into the test. (After 18 seconds, thermocouples began to fail and the data is suspect.) At the 6-foot (1.83 m) elevation, the measured cladding temperature was 1513.5 K (2264.6 degrees F). TRACE predicted 1554.2 K (2337.9 degrees F) using the Cathcart-Pawel (1977) correlation for metal-water reaction.

Figure 2 shows the results of the sensitivity of peak cladding temperature for the bundle used in FLECHT Test 9573 experiments with initial cladding temperature. In each case, the initial axial cladding temperature profile was scaled to that of Test 9573 to obtain the desired maximum cladding temperature at the start of each simulation. The reflood rate was assumed to be 1.1 inch/sec, consistent with Test 9573. At maximum initial cladding temperatures less than approximately 1200 degrees F (922 K), typical of those expected following the blowdown period of a LOCA, the peak cladding temperature remain below 1800 degrees F (1255 K). The predicted peak cladding temperature did not exceed 2200 degrees F (1477 K), unless the maximum initial cladding temperature was greater than 1600 degrees F. This is significantly higher than the initial temperatures that are expected to occur following the blowdown and refill periods of a LOCA.

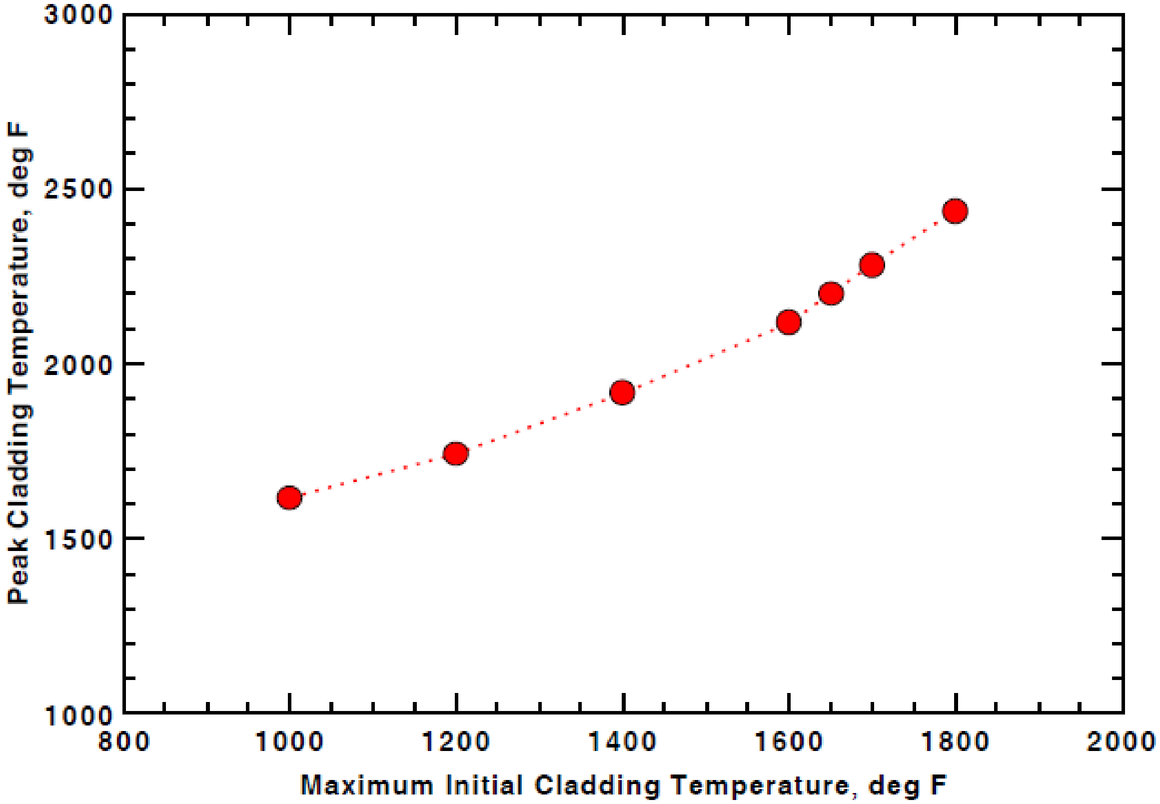

Figure 2. Sensitivity of Peak Cladding Temperature to Initial Cladding Temperature in a Simulated Zircaloy Clad Rod Bundle.

The reflood rate simulated in the calculations for Figure 2 was 1.1 inch/sec, in order to be consistent with the rate used in the actual experiment. Clearly, if coolant is denied to a rod bundle during reflood, the cladding will increase in temperature rapidly. The rate at which the cladding temperature increases depends on several parameters, as does the peak cladding temperature that is attained during a transient. As discussed previously, the peak cladding temperature depends on numerous other parameters including the rod power, coolant temperature, and pressure. This is because the temperature at a particular location on a rod depends on an energy balance. Ultimately the peak temperature depends on the local heat generation (decay heat from the fuel and metal-water reaction heat) and heat removal mechanisms (conduction away from the hot spot, convection to the coolant, and thermal radiation to the coolant or colder structures). Indeed, it is possible to cool a bundle and prevent the peak cladding temperature from exceeding 2200 degrees F (1477 K) with a zero reflooding rate if sufficient cooling is provided by other means.

Consider the TRACE model of the Zircaloy clad bundle that represented the bundle used in FLECHT Test 9573. Assuming an initial temperature profile with a maximum temperature of 1200 degrees F (922 K), a simulation was conducted with no liquid injection but with steam-only cooling of the bundle. Figure 3 shows the maximum cladding temperature as a function of time for a steam-only mass flow rate of 0.114 kg/s through the bundle. The peak cladding temperature obtained 1325.7 K (1927 degrees F). No liquid injection can be interpreted as a reflooding rate of 0.0 in/sec. Cooling was accomplished not by reflood of the bundle, but only by convective cooling to the steam. The cladding exceeded 1000 C (1832 degrees F), and thus metal-water reaction became a significant source of heat. Nevertheless, the peak cladding temperature remained below 2200 degrees F and an "autocatalytic" (runaway) oxidation did not occur.

The steam-only cooling calculation demonstrates that it is possible to cool a Zircaloy clad bundle without reflooding. Adequate cooling could be obtained by alternative heat transfer mechanisms. This indicates that specification of a minimum reflood rate, as requested by the petition, is not necessary. As long as sufficient cooling by the Emergency Core Cooling System (ECCS) is maintained, the peak cladding temperature can remain below the regulatory limit of 2200 degrees F (1477 K).

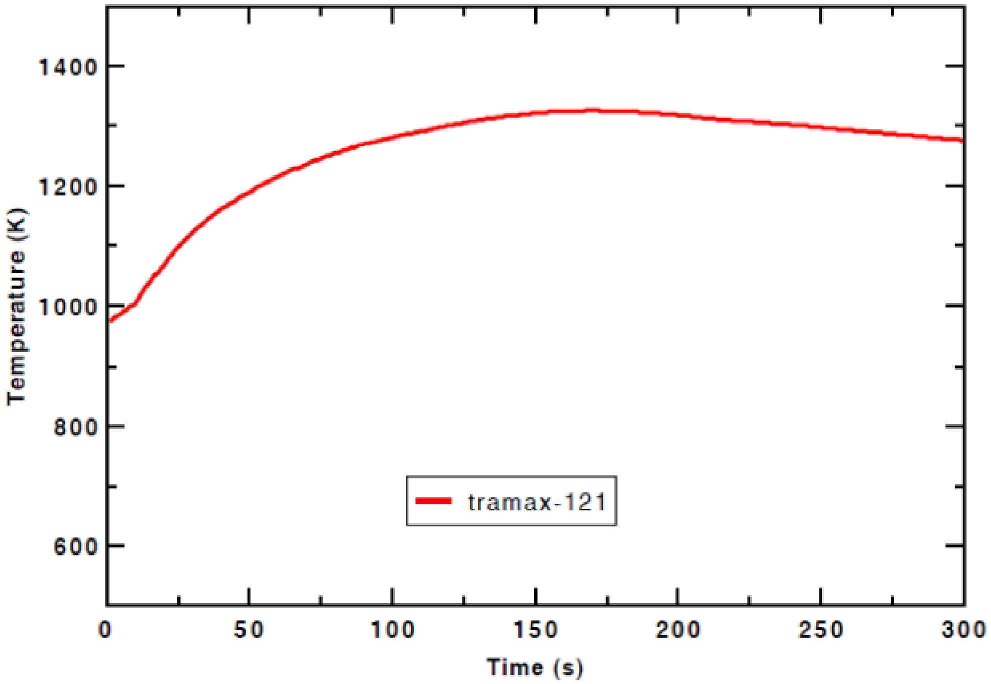

Figure 3. TRACE Simulation of Steam Cooling of a Zircaloy Bundle. (Mass flow rate = 0.114 kg/s, saturated steam at 0.42 MPa.)

Figure 3 demonstrates that the argument central to the petition's request that a minimum reflood rate be specified, is false. The petition's claim is:

> It would be reasonable to postulate that if run 9573 were repeated—with the same or a lower coolant flood rate, yet with lower initial cladding temperatures (that in the event of a LOCA, would occur at the beginning of reflood at current and/or proposed PWRs) and a lower power level (within the operational range of current and/or proposed PWRs)—that the fuel assembly would still incur autocatalytic oxidation and be destroyed, because run 9573 had the lowest flood rate of the four Zircaloy tests.

Figures 3 showed that if FLECHT Test 9573 were repeated with the same power level, the bundle would not have been destroyed as long as adequate cooling was maintained. The reflood rate is irrelevant. Thus, the results of the calculations presented in Figures 2 and 3 also demonstrate that the petition's claim that "it can be extrapolated from experimental data that, in the event a LOCA, a constant core reflood rate of approximately one inch per second or lower

(1 in./sec. or lower) would not, with high probability, prevent Zircaloy fuel cladding, that at the onset of reflood had cladding temperatures of approximately 1200°F or greater, from exceeding the 10 C.F.R. § 50.46(b)(1) PCT limit of 2200°F." is false.

5.0 Summary and Conclusions

The petition for rulemaking PRM-50-93/95 requests revisions to 10 CFR 50.46 "Acceptance criteria for emergency core cooling systems for light-water nuclear power reactors" and to 10 CFR Part 50, Appendix K "ECCS Evaluation Models" as well as associated regulatory guidance. The petition makes numerous references to FLECHT Test 9573, and claims that it was "highly probable that run 9573 incurred autocatalytic oxidation, because it had a low flood rate." Based primarily on this test and on the expectation that the NRU tests, if repeated, might behave similarly, the petition requests "that the NRC make a new regulation stipulating minimum allowable core reflood rates, in the event of a loss-of-coolant accident ('LOCA')."

This report has evaluated the claims in the petition related to specification of a minimum reflood rate and has reported on simulations of a Zircaloy clad bundle with a geometry and design as was used for FLECHT Test 9573. The calculations show the petition's claims to be false. Calculations with steam-cooling only showed that likewise, cladding temperatures in a Zircaloy clad bundle could be maintained within the regulatory limit. Cooling of a rod bundle depends on several parameters and heat transfer mechanisms, and not simply on the reflood rate. The staff thus concludes that the petition fails to provide sufficient information to justify revisions to 10 CFR 50.46 that would stipulate a minimum allowable core reflood rate.

6.0 References

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